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Early-stage design of municipal wastewater treatment plants- presentation and discussion of an optimisation based concept

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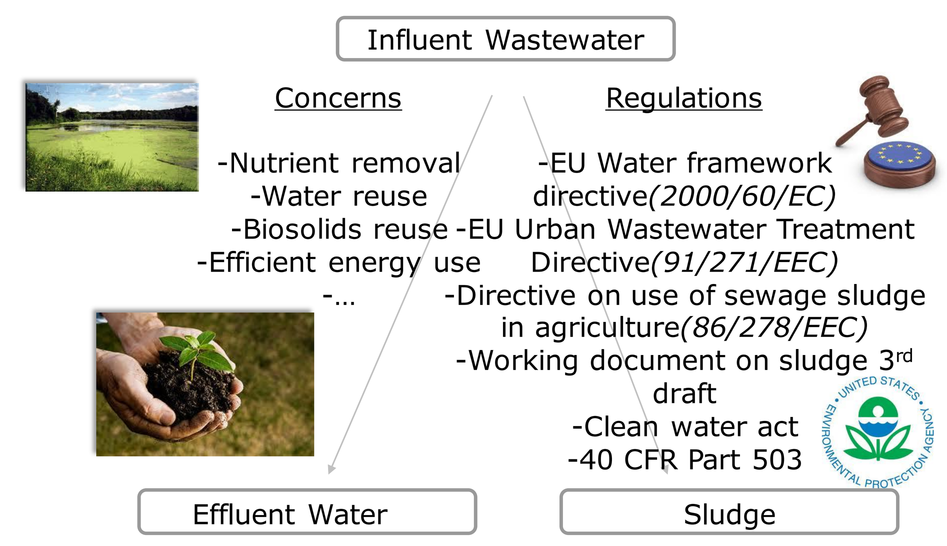
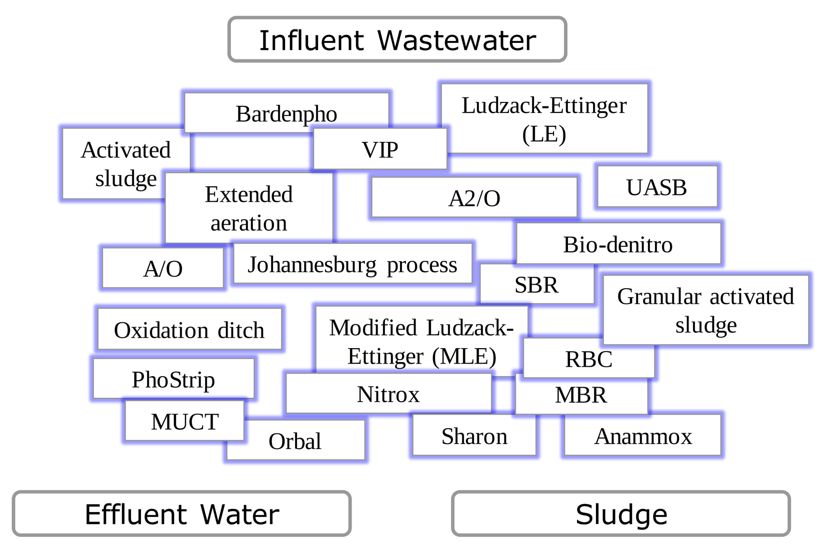
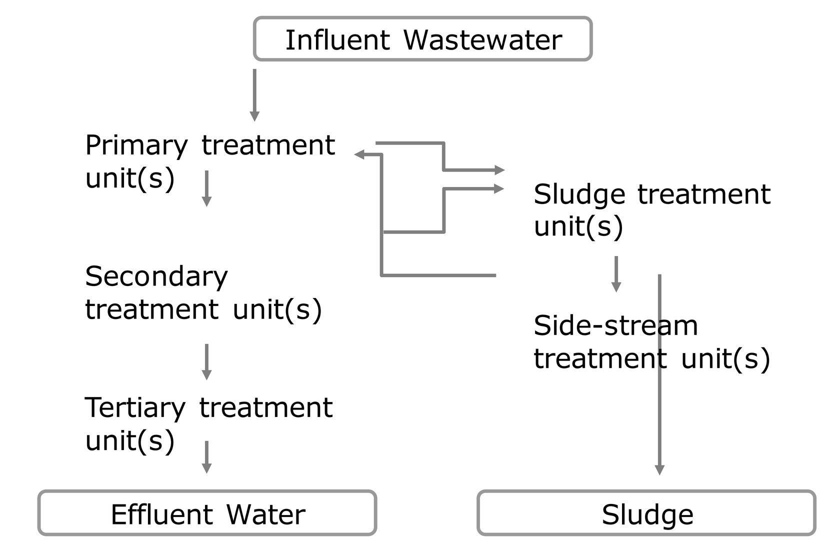
Introduction and Motivation

Wastewater treatment process synthesis: The selection of unit processes from several alternatives and interconnecting them to create the process flow diagram for a given wastewater characterization to meet predefined performance criteria.



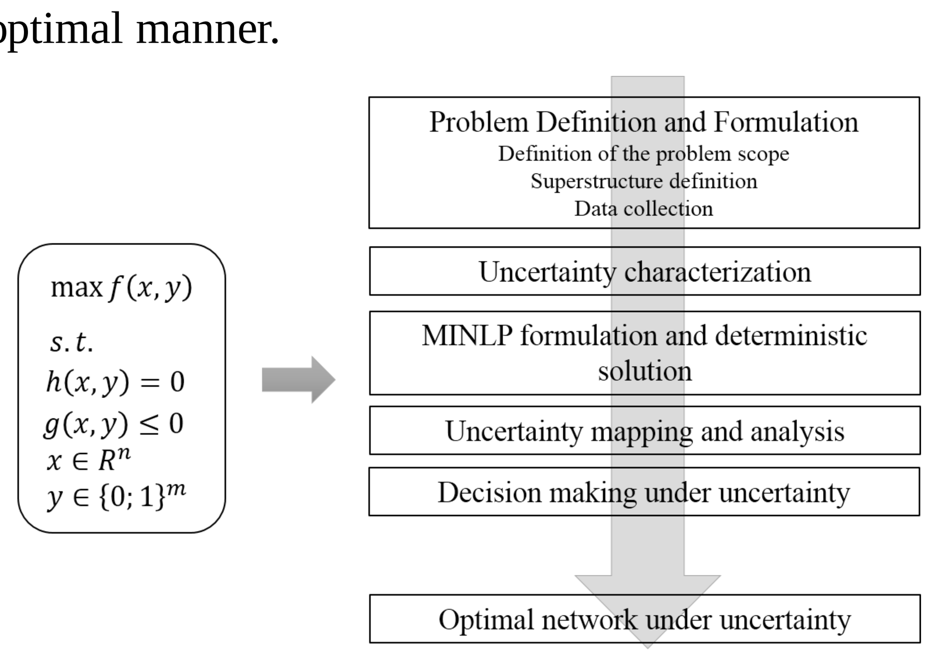




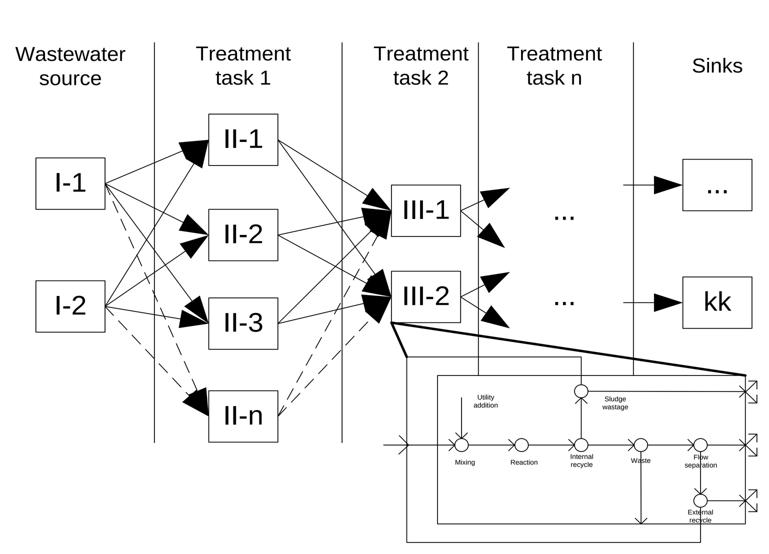
- The wastewater treatment process synthesis problem has evolved from being a simple technical problem to a complex integrated decision making task mainly because of the numerous aspects considered in the early stage decision making.
- The number of alternative wastewater treatment processes to choose from has increased significantly to meet increasingly stringent performance demands.
- Currently, the design approach takes values like environmental and cost issues, water reuse, by-product recovery and public impacts into account and makes decisions based on expert judgement and experiences [1].

Framework for synthesis and design

Objective of this study: To develop a superstructure based optimization approach which represents different aspects considered during early stage decision making with the help of mathematical programming to design / retrofit a domestic WWTP network in a novel and optimal manner.



The superstructure based optimization methodology for design of the optimal WWTP network [2]



A representative superstructure for WWT networks and generic process interval structure

The problem is defined by defining the wastewater characterization, effluent limitations and objective function.

Process intervals in the superstructure represent a treatment technology comprising several phenomena; mixing, utility addition, reaction and separation.

A robust design is only possible by taking the uncertainties into account, and therefore the framework includes the uncertainty analysis.

The optimum network under uncertainty is obtained after the solution of a stochastic MINLP problem

Phenomena	Equation
Mixing	$Fin_{i,kk}=\sum_{k} F_{i,k,kk}$
Utility addition	$Fmix_{i,kk}=Fin_{i,k}+\alpha_{i,kk}*R_{i,kk}$
Reaction	$R_{i,kk}=\sum_{ii}\left(\mu_{i,ii,kk}*F_{ii,kk}\right)$
Waste separation	$Freac_{i,kk}=Fmix_{i,kk}+\sum_{rr,react}\left(\gamma_{i,kk,rr}*\theta_{react,kk,rr}*F_{react,kk}\right)$
Flow separation	$Fw_{i,kk}=Freac_{i,kk}*\left(1-W_{i,kk}\right)$
	$Fout1_{i,kk}=Fw_{i,kk}*Split_{i,kk}$
	$Fout2_{i,kk}=Fw_{i,kk}-Fout1_{i,kk}-Frec_{i,kk}$
	$Fout3_{i,kk}=Freac_{i,kk}*SW_{kk}$
	$Frec_{i,kk}=\left(Fw_{i,kk}-Fout1_{i,kk}\right)*rec_{kk}$
	$FX_{i,k,kk}=FoutX_{i,k}*S_{k,kk}$
Activation	$y_{kk}*x_k^{LO}\le x_k\le y_{kk}*x_k^{UP}$
Logical cuts	$\sum_{kk} y_{kk}\le 1$

Explanations

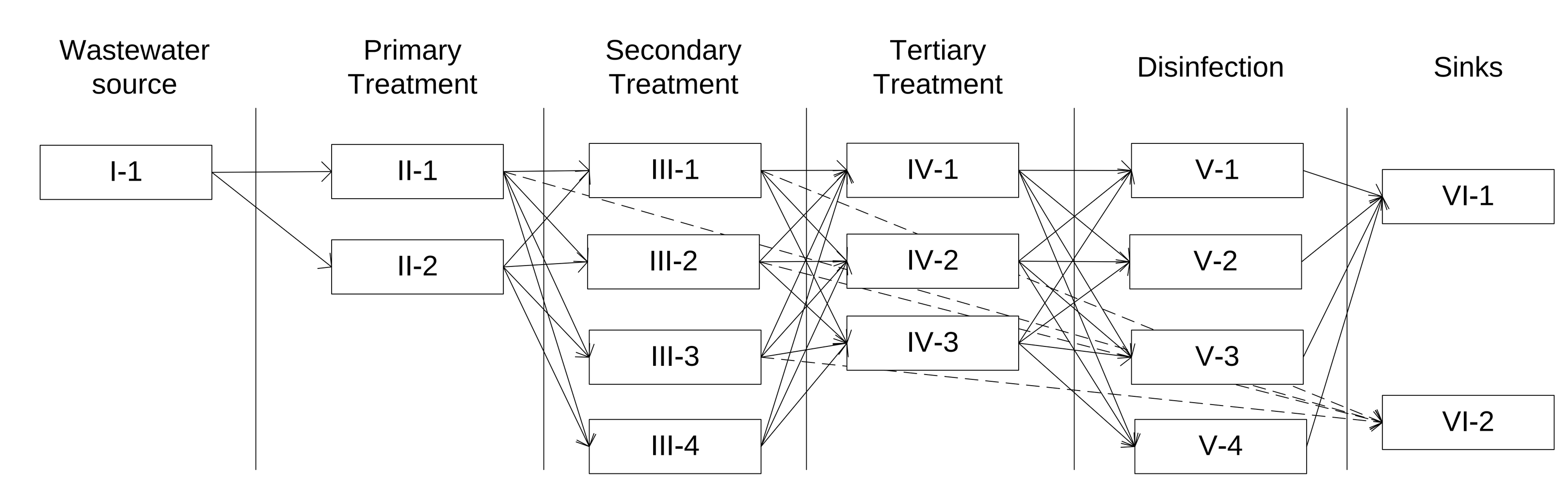
i,ii: component index
k,kk: process interval index
$Fin_{i,kk}$: inflow to the process interval
$F_{i,k,kk}$: inflow of component i to process kk coming from k
$Fmix_{i,kk}$: flow of after mixing
$R_{i,kk}$: utility flow
$\alpha_{i,kk}$: fraction of utility consumed
$\mu_{i,kk}$: specific consumption of utility
$Freac_{i,kk}$: flow after reaction
$\gamma_{i,kk,rr}$:matrix representing reaction stoichiometry
$\theta_{react,kk,rr}$:conversion efficiency of the key reactant react
$Fw_{i,kk}$: flow after waste separation
$W_{i,kk}$: waste split factor
Fout1,Fout2,$Fout3_{i,kk}$: Outlet streams from interval
$Split_{i,kk}$: flow split factor
SW_{kk}: Sludge Wastage flowrate ratio
$Frec_{i,kk}$: External recycle flow
rec_{kk}: external recycle ratio
X: 1,2,3 (representing three different outlet flow streams)
$S_{k,kk}$: binary variables containing superstructure information
y_{kk}: binary variable describing the process interval
x_k: variable bounded by upper and lower limits

Conclusions

- A mathematical programming concept has been introduced in this study to support the early stage decisions on WWTP network selection.
- By casting the problem as an optimization problem, the decision on which technology to employ is rendered on quantitative metrics which complements the experience based approach used today.
- The tool is developed to support and facilitate generation and evaluation of ideas for identifying optimal solutions to design new or retrofit existing WWTPs.
- The optimization problem not only gives the selected topology as an output but also enables the user to track the mass flow of components throughout the selected network and reports the cost breakdown information.

Case Study

Problem: Treatment of domestic wastewater comprising mainly COD, nitrogen and solids as pollutants [3].



Process interval	Definition
I-1	Wastewater source
II-1	Primary settler
III-1	Pre-denitrification with short SRT
III-2	Pre-denitrification with high SRT
III-3	Granular anaerobic treatment unit
IV-1	Partial nitrification
IV-2	Partial nitrification coupled with anaerobic ammonium oxidation
V-1, V-2, V-3	Disinfection by means of ozone, Chlorine and UV
II-2, III-4, IV-3,V-4	By-pass intervals
VI-1, VI-2	Sink intervals for water and sludge

Scenario definition: A deterministic problem is solved under three different scenario definitions. (1) operational cost minimization, (2) total annualized cost minimization (3) total annualized cost minimization with stricter N limitation.

Outputs of MINLP solution: All the scenarios by-passed the primary and tertiary treatment steps together with disinfection. The secondary treatment selection was the high SRT pre-denitrification technology for the first and third scenario and short SRT pre-denitrification for the second scenario. The fact that the short SRT system has a lower capital cost promoted its selection in the second scenario and the high SRT system was favoured due to its ability to remove nitrogen with higher efficiency.

Cost summary and performance evaluation for scenario 2

	Unit	Value
Selected alternative	-	I-1 / II-2 / III-1 / IV-3 / V-4 / VI-1 / VI-2
Aeration cost	Unit cost	111.421
Landfill cost	Unit cost	250.392
Biogas price	Unit cost	-
Electricity price	Unit cost	-
Capital cost	Unit cost	621.363
Objective function	Unit cost	983.176
Effluent COD	g COD/m^3	36.92
Effluent Total N	g N/m^3	12.92
Sludge Production	kg/d	2340.11

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